CHAPTER 4

Scientific Maturation of the ARM Program

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1. Introduction

There has been a tremendous evolution in both the technical and scientific capabilities of the Atmospheric Radiation Measurement (ARM) Program during its first 20 years. The Program was "born" in early 1990 and by mid-1992 the first observations were being collected at its Southern Great Plains (SGP) site (Stokes 2016). Over the next several years, additional instrumentation was deployed at the SGP site; by mid-1996 the site was considered fully instrumented, as per the scope that had been originally planned (U.S. Department of Energy 1990; appendix A, Stokes and Schwartz 1994), with the installation of the millimeter-wave cloud radar (MMCR; see Kollias et al. 2016). The following years saw the deployment of the first and second Tropical Western Pacific (TWP) sites at Manus and Nauru (Long et al. 2016) and the deployment of ARM instrumentation during the year-long Surface Heat Budget of the Arctic (SHEBA) experiment and at the North Slope of Alaska (NSA) sites (Verlinde et al. 2016). The programmatic aspects of ARM were evolving also in order to deal with the challenges of managing such a diverse program (Ackerman et al. 2016), especially as the ARM Program consolidated its airborne components into a facility (Schmid et al. 2006); the ARM Mobile Facility was conceived, developed, and deployed (Miller et al. 2016); and the Program was designated a Department of Energy (DOE) Science User Facility (Mather and Voyles 2013).

The scientific goals of the ARM Program from the beginning were to determine the effect of atmospheric composition and structure on the earth's radiative energy balance and to understand the processes that affected those atmospheric properties—with a particular emphasis on clouds (Ellingson et al. 2016; Stokes 2016; U.S. Department of Energy 1990). The fundamental goal of the ARM Program was to improve cloud parameterizations in general circulation models (GCMs) through improved understanding of cloud and radiation processes obtained from a combination of modeling and data analysis. The essential ARM questions were defined as follows:

1) If we can specify a cloud field, can we compute the radiative fluxes associated with that field?
2) If we can specify the large-scale atmospheric state variables, can we predict the cloud field properties associated with that state?

Answering the first question requires detailed knowledge of cloud properties, such as 3D structure, ice and liquid water path, hydrometeor concentration and size (and shape in the case of ice), and accurate, spectrally resolved, radiance and flux measurements. Answering the second requires knowledge of the 3D state properties and area-wide cloud field properties. These central themes defined the ARM measurement priorities but the scientific emphasis has continually shifted and evolved over the years,

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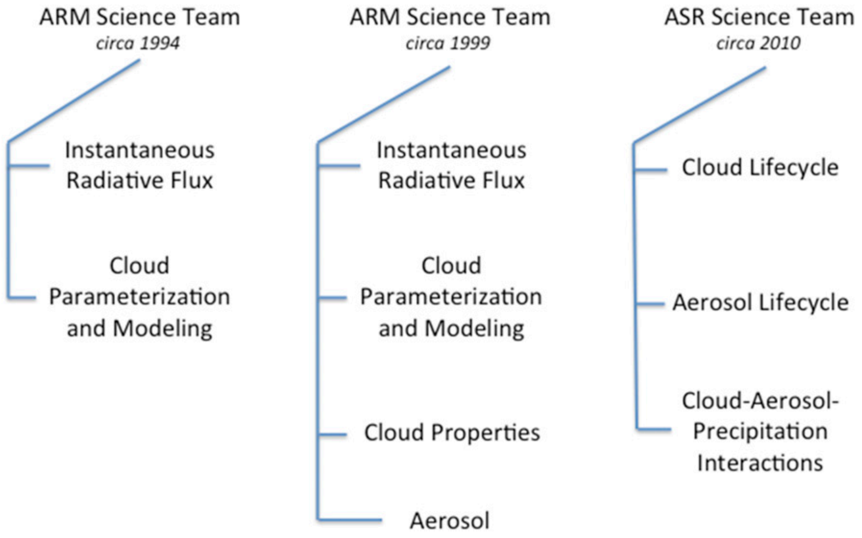

FIG. 4-1. The evolution of the working groups within the ARM (and later ASR) Science Team.

as have some of the details about how instruments are deployed and how data are processed and used.

From the beginning, DOE management looked to the ARM Science Team for input into the scientific priorities of the Program. In the ARM Program's formative stages, there was even a "surrogate" Science Team that was hand selected from the broader community to provide this input until the peer-review process had the time for proposals to be solicited, evaluated, and selected (Stokes 2016). To better facilitate communication among the different members of the ARM Science Team and to coordinate efforts of many individually funded research teams, working groups with specific foci were established. The Program benefitted as many grass-roots initiatives (ranging from ideas for field experiments to new instruments to deploy and scientific focus areas for the Program) were developed by ARM-funded scientists and flowed upward to ARM management after being vetted through the working groups. As the Program matured scientifically and programmatically, new challenges arose that required that the Science Team adapt; one way to illustrate this is by noting how the working groups evolved over time (Fig. 4-1). The working groups often had both formal and informal subgroups within them to focus on more specific topics. The working group structure worked extremely well for both coordinating the research within the group, but also for aggregating recommendations from individual principal investigators (PIs) to ARM management on how to improve the infrastructure to better serve the needs of the ARM Science Team.

After the creation of the formal Science Team, a subset of this community was selected to serve as the Science Team Executive Committee (STEC). Typically, the chairs of the working groups were on the STEC, which was augmented with other scientists from the program to provide additional perspective. The STEC met regularly with infrastructure managers and DOE management to discuss the Program's scientific direction and to prioritize the recommendations that were made by the working groups. This was especially important in the early years. The STEC would evolve into the Science and Infrastructure Steering Committee (SISC) after the ARM infrastructure was designated as a DOE User Facility (Ackerman et al. 2016).

The ARM Program also had three Chief Scientists to help guide it during its formative phase through its maturity: Gerry Stokes from 1990 to 1998, Tom Ackerman from 1999 to 2004, and Warren Wiscombe from 2005 to 2009 (Fig. 4-2). The Chief Scientists worked closely with DOE and infrastructure management to advance ARM science, helped to organize and conduct the annual Science Team Meeting in the spring, provided input on infrastructure priorities from the scientific perspective, and served as the ambassadors of the Program. The ARM Chief Scientists worked with the STEC to develop the ARM Science Plan in 1996 (U.S. Department of Energy 1996, appendix B therein) and its update in 2004 (U.S. Department of Energy 2004, appendix C therein), and with the SISC to develop the Science Plan for the Atmospheric System Research (ASR) program that was created in 2010 (more on ASR at the end of this chapter).

The ARM Program's scientific growth was tremendous. One simple metric of this is the number of peer-reviewed journal articles supported by ARM over the last 20 years (Fig. 4-3). Other measures of the scientific impact of the ARM Program are the increase in the number of high-quality science proposals submitted to

FIG. 4-2. The Chief Scientists of the ARM Program: (left to right) Gerry Stokes, Tom Ackerman, and Warren Wiscombe.

DOE each year, and the diversity of the topics spanned by the published peer-reviewed papers in the later years (relative to the earlier time periods) with ARM support. It is important to note that the plateau seen in Fig. 4-3 is largely due to the plateau in the scientific funding that had occurred by the late 1990s.

This chapter highlights some of the broad scientific accomplishments of the ARM Program during its first 20 yr. This story could have been told multiple ways. We have elected to organize the story into thematic sections; while the presentation of each section is largely chronological, much of the scientific work was occurring in parallel. Chapters 13 through 30 of this monograph provide much more detail on the scientific accomplishments in the various areas than could be covered here.

2. Using ARM observations to improve our understanding of radiation, aerosol, and clouds

a. Making a good measurement

Deploying automated instruments into these unique locations to collect long-term datasets challenged the Program in many ways. Prior to ARM, most complex observational datasets collected in the field were limited to relatively short time frames of several weeks to perhaps several months. The PI and cohorts would deploy the instruments, collect the data, and then spend potentially many months calibrating and analyzing the data before they were made available to the community. Often, it would also be difficult to collect the different datasets from the various PIs, and it would be challenging to sort out the various differences in the way the different PIs quality-controlled and organized their data. The ARM Program's decision to collect long-term datasets precluded this model, and thus the Program decided to make the data available almost immediately[1] after it was collected and enlist the help of the ARM Science Team and site scientists to help with the quality control (Peppler et al. 2016).

However, first the instruments had to be able to run continuously; the ARM Program's Instrument Development Program (IDP; Stokes 2016) invested heavily to quickly advance several remote sensing systems so that they could run in an unattended way. Three of the most obvious examples are the Atmospheric Emitted Radiance Interferometer (AERI; Turner et al. 2016b), the MMCR (Kollias et al. 2016), and the Raman lidar (Turner et al. 2016a); however, instruments such as the micropulse lidar (MPL; Campbell et al. 2002), microwave radiometer (MWR; Liljegren and Lesht 1996), and many others benefitted from ARM investments to make them more robust for long-term operations (U.S. Department of Energy 2004). However, the investments in these instruments did not immediately result in usable datasets; it often took multiple years of interactions between observationalists and the instrument mentors before the data from an instrument were useful for the modeling community.

Just because an instrument is running does not ensure that its data are useful; there must be calibration methods in place to ensure that the data are accurate and the uncertainties quantified. The long-term operational paradigm—together with the deployment of instruments that measured similar or complementary geophysical

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[1] The Internet was in its infancy when the ARM Program started, and thus the phrase "almost immediately" has different connotations depending on the reference point. In the mid-1990s, data collected at the SGP site were delivered to ARM Science Team members within a week of collection, and data from the TWP sites were typically delivered every few months due to the lack of efficient and affordable communication with the remote sites. By the early 2000s, almost all the data collected from ARM instruments were made available to the ARM Science Team within 2 days.

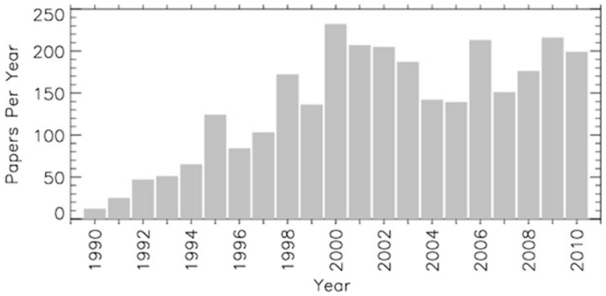

FIG. 4-3. Number of papers published in peer-reviewed journals supported by the ARM Program from its inception until 2010. Data are from the ARM publication database.

variables that could be intercompared, perhaps using a model as a transfer standard, via quality measurements experiments (QMEs; Peppler et al. 2016; Turner et al. 2004)—highlighted many issues associated with calibration that were not well understood before. Many of the calibration issues were first identified from longer-term analysis, and then intensive observation periods (IOPs) were used to further elucidate the source of the error in the calibration method and develop improved methods.

One example of this was the development of an automated method to maintain the calibration of the MWRs (Liljegren 2000), which drew heavily from results garnered from the water vapor IOPs (Turner et al. 2016b) that, among other things, investigated the various error sources that might impact the calibration of the MWRs (Han and Westwater 2000). A second example was the discovery that there were systematic errors in radiosonde relative humidity measurements that were associated with how the manufacturer was calibrating them in batches (Liljegren and Lesht 1996; Turner et al. 2016b); prior to this, radiosondes were typically assumed to be the gold standard for profiles of water vapor and temperature and this ''batch'' behavior was unnoticed because of the short duration of previous field campaigns. A third example is the need for the Radiometric Calibration Facility at the SGP site, which was built in the late 1990s to calibrate dozens of broadband solar and infrared radiometers simultaneously against radiometric standards (Michalsky and Long 2016), thereby ensuring consistent calibration across large numbers of instruments that are deployed at the many ARM sites.

The investment in hardening the instruments and running them autonomously for long time periods, and especially the development of improved calibration approaches that were subsequently applied to the long-term measurements, made the ARM datasets uniquely valuable. ARM also deployed complimentary instruments, such as the laser ceilometer and the MMCR to measure different aspects of cloud structure, which led to the development of more sophisticated analyses and cleaner interpretation of atmospheric structure and phenomena. The standardization of the format of the data files using netCDF tools and an easy-to-use data archives for storage also contributed to the long-term success of ARM (McCord and Voyles 2016). These are considered some of the primary technical accomplishments of the ARM Program, which subsequently led to many of the scientific accomplishments below.

b. *Instantaneous radiative fluxes in the clear sky*

One of the primary ARM goals was to understand the interaction of radiation with aerosols and clouds. However, early investigations showed that more fundamental clear-sky radiative transfer issues needed to be resolved first before significant progress with clouds could be made; these issues are discussed in detail in Ellingson et al. (2016).

Early on, the Instantaneous Radiative Flux (IRF) working group, building on previous radiation-focus programs (such as the Spectral Radiance Experiment) to address the findings of the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) effort (Ellingson et al. 2016), undertook a number of radiative closure studies (Mlawer and Turner 2016) in which investigators used ARM observations of parameters such as temperature and humidity profiles as inputs to a radiative transfer model, and then compared the radiation calculations to radiation measurements at the surface. An important tool in these early clear-sky infrared closure studies was the AERI (Knuteson et al. 2004a,b; Turner et al. 2016b). The AERI provided high-spectral-resolution radiance measurements at infrared wavelengths. Comparisons with simulations from the AER line-by-line radiative transfer model (Clough et al. 1992) revealed that errors and uncertainties in water vapor measurements were a limiting factor in constraining surface infrared fluxes (Revercomb et al. 2003).

The problems with water vapor profiles led to an intensive study of water vapor measurements including a series of field campaigns beginning with the Water Vapor Intensive Operation Period in 1996 (Revercomb et al. 2003; Turner et al. 2016b). These studies led to innovative techniques for measuring water vapor including use of a two-channel microwave radiometer to mitigate differences across batches of radiosondes (Turner et al. 2003), use of the AERI to retrieve profiles of water vapor and temperature in the boundary layer (Feltz et al. 2003), and the use of the Raman lidar to obtain more continuous water vapor profiles (Turner and Goldsmith 1999).

In addition to these observation-oriented activities, there was also a great deal of activity related to the improvement of infrared radiative transfer models going on within the IRF working group. Particular areas of focus were improvements in the water vapor continuum, which led to the ability to compute downwelling radiation to better than 1.5 W m^{-2} (Tobin et al. 1999; Turner et al. 2004). These improved high-spectral-resolution line-by-line radiative transfer models were used to develop an infrared radiative model suitable for climate models (Mlawer et al. 1997; Mlawer and Turner 2016). The Rapid Radiative Transfer Model (RRTM) represented a significant improvement in accuracy over radiative transfer models used within GCMs at the time and was a direct outcome of the strong emphasis that ARM placed on clear-sky infrared radiative transfer through the 1990s (Iacono et al. 2000).

As in the infrared, there were challenges in closing the surface radiation budget in the solar shortwave part of the spectrum. Well-calibrated cavity radiometers gave confidence in measurements of the direct solar beam; however, constraining the diffuse solar flux proved to be more challenging (Dutton et al. 2001; Michalsky and Long 2016). And as with efforts to close the longwave radiation budget, there were also significant uncertainties in environmental parameters required to calculate shortwave fluxes. In the clear (or noncloudy) sky, key environmental uncertainties were the surface spectral albedo, the distribution and radiative properties of aerosols, and the absorptivity of gaseous constituents (Kato et al. 1997; Michalsky and Long 2016).

Characterization of the surface spectral albedo is complicated because the downwelling solar flux is sensitive to the albedo over a region spanning on the order of a few kilometers and the albedo is typically heterogeneous spatially (on land) and variable in time. Early calculations tended to gloss over these effects but they do introduce errors in radiation calculations. The realization of these effects, and subsequent aerial measurements to investigate the spatial distribution of the albedo over different surfaces, led to the quantification of these uncertainties and provided the means to reduce their magnitude (Michalsky et al. 2003).

Discrepancies between modeled and measured shortwave fluxes at the surface in the mid-1990s pointed to a large amount of anomalous solar absorption in the column (e.g., Kato et al. 1997; Valero et al. 1997; Zender et al. 1997). This effect was particularly pronounced in cloudy skies but there were also challenges in achieving closure in clear skies. There was a great deal of speculation regarding the source of this apparent absorption: aerosols, gaseous species, or measurement errors. The challenges in achieving shortwave closure in both clear and cloudy skies led to the ARM Enhanced Shortwave Experiment (ARESE) aircraft experiments in 1995 and 2000 (Valero et al. 2003; Schmid et al. 2006; Michalsky and Long 2016), and to improvements in the measurements of solar diffuse radiation (Michalsky et al. 2005). The results from the ARESE-2 experiment demonstrated that, while there is still a small bias between the observed radiative flux and the computed flux, the bias could be explained largely by the uncertainties associated with the measured flux, mismatch between the ground and airborne radiometers, and uncertainties in both the radiative transfer models and the inputs used to drive it and in particular surface albedo (Ackerman et al. 2003; Li 2004).

c. *Aerosol optical properties*

Reducing uncertainties in shortwave measurements required developing a good understanding of the optical properties of aerosols. A great deal of work on aerosols initially in ARM was focused on the direct effect of aerosols on, primarily, shortwave radiation. Measurements of aerosol properties included both in situ observations at the surface and remote sensing. Obtaining the vertical profile of aerosol optical properties was, and remains, a challenging measurement problem.

ARM sites include an Aerosol Observing System (AOS) that provides in situ measurements of aerosol optical and microphysical properties (Sheridan et al. 2001). The suite of AOS instruments provides a continuous view of the aerosol population and optical properties at the surface, but says nothing directly about the profile of aerosol properties. In a daytime convective environment, it is often assumed that aerosols are well mixed through the boundary layer and that the surface-based observations are representative of the aerosol aloft; however, even in that case, one must account for the dependence of aerosol optical properties on relative humidity as many species of aerosols grow hygroscopically as relative humidity increases.

Several tools have been used to extend aerosol measurements away from the surface beginning with passive and active remote sensing. The primary measurement required for evaluating the direct effect of aerosols on shortwave radiation is the total column aerosol optical depth (AOD), and the primary tool to measure AOD at the ARM sites is the Multifilter Rotating Shadow Band Radiometer (MFRSR; Harrison et al. 1994). The autonomous derivation of AOD from continuous MFRSR irradiance measurements requires careful cloud screening. This process is now largely automated but can still be difficult in some environments (Michalsky et al. 2010).

The MFRSR provides the total AOD but it does not provide any information about the vertical distribution of aerosols. The vertical distribution is not necessary to evaluate the impact of aerosol on the surface radiation budget but it is important for determining the profile of absorption, and therefore radiative heating, within the column, and it is critical for determining the effect of aerosols on clouds.

Lidars are sensitive to aerosols and can be used to obtain information about vertical profiles. However, a simple elastic scatter lidar cannot provide optical extinction (scattering + absorption) without making significant assumptions, the main assumption being that the extinction-to-backscatter ratio is constant through the troposphere (e.g., Welton 2000; Schmid et al. 2006). The ARM Raman lidar includes measurements of total backscatter as well as profiles of Raman scattering by nitrogen, which provides the means of deriving aerosol extinction (Turner et al. 2002, 2016a). Using the SGP Raman lidar observations, Ferrare et al. (2001) found that the extinction-to-backscatter ratio cannot be considered constant more than 30% of the time.

From 2000 to 2007, a small aircraft outfit with basic aerosol in situ instruments was flown over the ARM SGP site several times per week. These flights provided an important record of the variability in the aerosol vertical structure up to about 5 km above sea level (Andrews et al. 2004). The size of the aircraft and the goal of flying on a routine basis significantly limited the number of instruments the aircraft could carry as part of the In Situ Aerosol Profile extended campaign. To more fully test the relationship of surface observations to the column, in 2003 the ARM Program conducted an expansive Aerosol IOP (Ferrare et al. 2006; McComiskey and Ferrare 2016). This IOP, together with some smaller IOPs and long time series analysis at the SGP site, concentrated heavily on improving measurements of aerosol absorption, understanding processes that affect the absorbing properties of aerosol, and quantifying the radiative impact of these aerosols (e.g., Andrews et al. 2004, 2011; Sheridan et al. 2005; Arnott et al. 2006). Comparisons of aerosol extinction profiles observed by the Raman lidar, airborne sun photometers, and in situ scattering and absorption measurements demonstrated initially large differences (Schmid et al. 2006), but the upgrade in the Raman lidar (Turner et al. 2016a) resulted in much better agreement with airborne sun-photometer extinction measurements (Schmid et al. 2009).

d. The distribution and radiative impact of clouds

From the beginning of the ARM Program, there were several tools available for obtaining cloud macrophysical (location) and microphysical (particle size, shape, phase, number concentration, etc.) properties. The MPL (Campbell et al. 2002) and laser ceilometer both provided cloud-base information, sometimes for multiple cloud layers if the layers were optically thin, while instruments like the Whole Sky Imager (WSI), which was used by ARM from the mid-1990s until it was retired in 2004 (Sisterson et al. 2016), and the Total Sky Imager (TSI), which was used by ARM from 2000 until present, provided a hemispheric view of cloud cover (Long et al. 2006). Passive longwave or shortwave broadband measurements could also be used to provide information about the optical properties of both liquid and ice clouds in combination with microwave (e.g., Dong et al. 1997) or lidar (Comstock and Sassen 2001) measurements. However, work on clouds began to accelerate in late 1996 when the MMCR was deployed at the ARM SGP site (Moran et al. 1998; Kollias et al. 2016).

The MMCR was a 35-GHz pulse-Doppler radar that provided vertical profiles of reflectivity and Doppler velocity from cloud and precipitation particles. Because of its short (8.6 mm) wavelength, the radar was sensitive to most cloud particles, even in the presence of light to moderate precipitation (which attenuates the MMCR's signal), although it was not always sufficiently sensitive to detect very small (smaller than the order of 10 μm) cloud droplets because of the strong sensitivity (D^6) of the radar backscatter to particle diameter D. The MMCR is very complementary to lidars, which are particularly sensitive to small particles with high number density. Together, the MMCR and MPL provided unprecedented information about vertical cloud structure on a continuous basis (e.g., Mace and Benson 2008). This information was made readily accessible to the broad community through the Active Remote Sensing of Cloud Layers (ARSCL) cloud mask, which quickly became one of the most widely used ARM data products (Clothiaux et al. 2000; Kollias et al. 2016).

The MMCR also gave rise to a variety of cloud property retrievals based on the radar observations (reflectivity and Doppler velocity) alone, or in combination with passive radiometers or in combination with other instruments. Much of the work over the first decade of the MMCR operation focused on single-phase liquid (e.g., Dong and Mace 2003; Turner et al. 2007a) or ice clouds (e.g., Mace et al. 1998; Comstock et al. 2007). Mixed-phase conditions are commonly found in deep convection and in Arctic stratus; however, there was a strong sense in the community that progress had to be made with the single-phase clouds before the more challenging mixed-phase clouds could be tackled in earnest. The availability of a large range of different complementary observations that provided information on cloud macrophysical and microphysical properties resulted in a huge number of different retrieval algorithms being developed; this history is captured by Shupe et al. (2016).

The improvements in cloud retrievals allowed the Program to also investigate how changes in the aerosol concentration impacts cloud properties (i.e., the aerosol indirect effect). ARM scientists were the first to measure the aerosol indirect effect using ground-based sensors (Feingold et al. 2003); they also developed methods to derive information on cloud condensation nuclei from ARM observations (Feingold et al. 1998; Ghan et al. 2006), quantified aerosol hygroscopicity using in situ and remote sensing data (Pahlow et al. 2006), and performed experiments to quantify the aerosol impact on cloud properties in stratiform (e.g., McComiskey et al. 2009) and cumulus (e.g., Berg et al. 2011) clouds.

e. Three-dimensional radiative transfer

From the very beginning of ARM, the Program supported efforts to better characterize and model 3D radiative transport in various media (e.g., Davis and Marshak 2001; O'Hirok and Gautier 1998), to develop improved 3D radiative transfer models and intercompare these models with each other and observational datasets (e.g., Barker and Marshak 2001; Han and Ellingson 2000; Kablick et al. 2011), and to determine how well 1D solar radiative transfer models handle unresolved clouds in cloud resolving model output (Barker et al. 2003). Much of the ARM Program's success in 3D radiative transfer is neatly summarized in the textbook edited by Marshak and Davis (2006).

f. Cloud modeling

One of the central goals of the ARM Program is to improve the representation of clouds and their radiative effects in climate models. This goal could have been handled by simply making ARM data available in anticipation that the modeling community would use the data, but the DOE program managers decided to not leave this to chance. Instead, modeling activities were built into ARM from the beginning. The general strategy has been that of the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (Randall et al. 2003)—namely, to use observations, and sometimes numerical weather prediction model reanalyses, in the region around an ARM site on the scale of a GCM grid box to provide the initial dynamical forcing conditions for a single column model (a single column from a GCM; Zhang et al. 2016) or a cloud ensemble or cloud-resolving model (Randall et al. 1996, 2003; Krueger et al. 2016). The model is then run and the output cloud field and other fields are compared with observations—either direct comparison of time series or statistical distributions.

The development of model forcing data using the constrained variational analysis technique is another of the primary accomplishments of the ARM Program (Zhang and Lin 1997; Zhang et al. 2016). This model forcing dataset is dependent on having high temporal resolution profiles of temperature, humidity, and wind that are typically provided by radiosondes, but uses surface and top-of-the-atmosphere measurements to constrain the energy and water sources and sinks (with precipitation being perhaps the most important sink).

Unfortunately, the 2–4 radiosonde launches per day, typical for ARM sites, are often not adequate for properly capturing and representing the advective tendencies of temperature and water vapor to get the large-scale forcing dataset. Therefore, ARM has a long history of conducting IOPs in which the frequency of radiosonde launches is increased to 8 per day at 4 to 6 sites around the SGP domain to support modeling activities (Zhang et al. 2016). The first of these so-called SCM IOPs was held early in 1995, just a few years after the beginning of data collection, and there have been many campaigns since focused on supporting modeling activities. Variational forcing datasets have also been created for a number of major field campaigns away from the SGP site, such as in the cases of the Mixed-Phase Arctic Cloud Experiment (M-PACE; Verlinde et al. 2007) and the Tropical Warm Pool International Cloud Experiment (TWP-ICE; May et al. 2008). Additionally, a continuous forcing dataset has been developed (Xie et al. 2004) that allows long-term SCM or cloud-resolving model simulations to be conducted and evaluated against ARM observations (e.g., Henderson and Pincus 2009) or can evaluate reanalysis data over multiple years (Kennedy et al. 2011).

These forcing datasets are critical inputs for the modeling community, allowing single-column models, cloud-resolving models, and large-eddy simulation models to be run over the ARM site in a manner that allows output from these models to be evaluated with other ARM observations (e.g., cloud fraction profiles). The M-PACE modeling studies (e.g., Klein et al. 2009; Morrison et al. 2009) illustrated the challenges in simulating mixed-phase clouds, the critical need to have accurate ice nuclei (IN) concentration observations, and the importance of having accurate cloud macro- and microphysical properties in the Arctic environment. The uncertainties in the observed IN concentrations and processes associated with ice nucleation have proved to be a central issue for analyses of M-PACE and the Indirect and Semi-Direct Aerosol Campaign (ISDAC; McFarquhar et al. 2011) data, and continue to be a central issue in the study of arctic clouds. TWP-ICE led to a variety of studies related to precipitation (Fridlind et al. 2011), diabatic heating (Xie et al. 2010a), and the effects of model resolution (Boyle and Klein 2010), among others. TWP-ICE also demonstrated that cloud-resolving models overpredict updraft speeds and reflectivities in convection (Varble et al. 2014), and that uncertainty in the measurement of precipitation compromises the ability of SCMs to respond correctly in weakly forced environments (Davies et al. 2013).

Other modeling activities with roots in the ARM Program are the Cloud-Associated Parameterizations

Testbed (CAPT; Phillips et al. 2004; Williamson et al. 2005) and the ''super-parameterization'' framework (Khairoutdinov et al. 2005; Ovtchinnikov et al. 2006). In the CAPT framework, a climate model is initialized and run like a numerical weather prediction model and then evaluated against observations, typically over an ARM site. The object of the CAPT framework is to evaluate the tendency of the climate model to develop errors over short time scales (a few days). Additionally, the ARM observations were used to help evaluate parameterizations in the European Center for Medium-Range Weather Forecasts (ECMWF) model (Ahlgrimm et al. 2016); both this activity and the CAPT activity helped make progress on the second major ARM question: ''If the large-scale variables are specified properly in the model, will it predict the proper cloud properties?'' In the superparameterization (which is also known as the multiscale modeling) framework, a two-dimensional cloud-resolving model is embedded in each grid cell of a GCM. This technique is computationally expensive but much less expensive than a full global cloud-resolving model while providing information about subgrid-scale cloud structure and a better representation of a large number of moist processes.

g. Site-specific science

The SGP site (Sisterson et al. 2016) was the first CART site. Its designation as a test bed was appropriate both because of the role the site served to evaluate models and because the SGP also served as a testing ground for other sites. Most of the activities described so far in this chapter were carried out—or first carried out—at the SGP site. But ARM expanded to other sites to sample other regions of the world, some of which were permanent and others of more limited duration.

After the SGP, the next site to be installed was the TWP site on Manus Island, Papua New Guinea, in 1996 (Mather et al. 1998; Long et al. 2016). This was followed by the NSA site in Barrow, Alaska, in 1998 (Stamnes et al. 1999; Verlinde et al. 2016). The Manus and Barrow sites did not have all the instruments found at the SGP, but they had a critical core set including the MMCR, MPL, AERI, MWR, and radiosondes. With the establishment of the Manus and Barrow sites, ARM was collecting measurements in three major climate regimes. These sites greatly expanded the range of science topics that could be addressed with ARM data.

At Manus, and later at the ARM TWP sites deployed on Nauru Island and at Darwin, Australia, the science focus was on tropical maritime convection and associated cirrus outflow (Long et al. 2016). Although the SGP is convectively active during part of the year, the tropical atmosphere and the associated convection are inherently different than found at the SGP. In the tropics, the thermal structure varies very little in comparison with the midlatitudes and convection tends to be much more stochastic in nature, although it does organize on large scales by tropical waves such as the Madden–Julian oscillation and on longer time scales such as El Niño–Southern Oscillation (ENSO). Tropical phenomena such as ENSO have a strong influence on the global circulation so understanding the physical processes that affect these phenomena is critical for improving simulations of global climate.

At the NSA site, stratiform clouds are prevalent, and these clouds very often are mixed-phase clouds (Verlinde et al. 2016). The dynamics and processes at work in these mixed-phase Arctic clouds are not well understood and only recently have there been good measurements of these cloud systems. These new observations suggest that there are many processes operating in a fine balance that enable mixed-phase stratiform clouds to exist for hours to days at a time (Morrison et al. 2012). The rate at which the ice in the Arctic Ocean has been decreasing over the last decade has exceeded model predictions (Stroeve et al. 2012), and thus it is important to understand the role that clouds, aerosols, and the atmospheric thermal structure play in this change. Additionally, the small amount of precipitable water vapor (PWV) in the winter at the NSA site results in the thermal infrared spectrum being much more transparent than at other ARM sites. ARM observations in the Arctic have been used to evaluate and improve spectral radiative transfer models in both the traditional 8–12-μm infrared window and the less transparent 18–25-μm window (Tobin et al. 1999; Delamere et al. 2010), which was one of the original goals of the research at the NSA site (Stamnes et al. 1999).

The observations made at the ARM sites are very complementary to satellite observations; the ARM observations are much more detailed with higher vertical and temporal resolution and capture the diurnal cycle well, whereas the satellite observations provide a much larger spatial view. Hence, satellite observations have always been very important for ARM, and ARM's observations have been immensely valuable for the various satellite programs (Marchand 2016).

3. Shifting strategy

With the establishment of the full set of fixed-location sites and the development of an integrated measurement and modeling strategy, the ARM Program evolved to become a fully mature scientific program. The TWP Darwin site was deployed in 2002, and the ARM measurement infrastructure had reached a plateau. All of the fixed sites were up and running, there were no plans for additional permanent observation facilities and, with a few exceptions, the core set of measurement capabilities had been implemented at all the measurement sites. It took a decade after the first measurements were made at the SGP site to reach this point, which was coincidentally the originally anticipated length of the ARM Program. The extended deployment schedule was primarily driven by budget considerations, but there were many lessons to be learned and difficult problems to solve in getting the Program to this point that also took time.

Throughout the first decade of the ARM Program, the Science Team and the infrastructure were tightly coupled. This coupling manifested itself in the planning and implementation of field campaigns, optimization of instrument configurations, and the development of advanced data products. However, this tight coupling also tended to limit the breadth of users of ARM data. ARM data were publicly available from the ARM Data Archive very early in the Program (McCord and Voyles 2016); however, there was a sense at the time by some scientists outside of ARM that ARM was a closed program. This perception was likely due in part to the close coupling between the Science Team and the infrastructure. This situation changed when ARM was designated a User Facility (Ackerman et al. 2016). This designation reinforced the notion that ARM data are useful for a much wider community than just the ARM Science Team, and led to a wider range of science being conducted with ARM data.

a. ARM science program and its relationship with the new ARM facility

In many respects, there were no significant changes in the organization of the ARM science program during the first years after ARM was designated as a User Facility (i.e., from 2004 to 2008). There was a shift away from clear-sky radiative studies toward evaluating radiative and microphysical properties of clouds and aerosols, and improving the representation of clouds and aerosols within climate models. Scientific understanding continued to evolve, and during this period the Science Team began to consider the need to expand the core measurement capabilities to obtain more detailed information on cloud and aerosol properties and to obtain some spatial information of these properties, with the focus of improving the representation of clouds in GCMs.

Research investigating cloud properties and processes accelerated greatly during the 2004–10 period. The cloud radar and its primary data product ARSCL were mature (Kollias et al. 2016) and a large number of PIs within the ARM Program were working on cloud property retrieval algorithms (Shupe et al. 2016). Major accomplishments included a better understanding of the vertical distribution of clouds and their radiative effects (Mace and Benson 2008; Mather and McFarlane 2009), and microphysical properties of low liquid water stratus clouds (e.g., Dong and Mace 2003; McComiskey et al. 2009) and cirrus clouds (e.g., McFarquhar et al. 2007; Deng and Mace 2008; Protat et al. 2010). Mixed-phase clouds present a particular set of measurement challenges, but a great deal of progress was also made using radar Doppler spectra, depolarized lidar backscatter profiles, and spectral infrared radiances (e.g., Turner 2005; Shupe et al. 2008; de Boer et al. 2009; Luke et al. 2010). The ARM Program began saving Doppler spectra from the cloud radars around 2000; this was a seminal moment for the Program because it provided a tremendous increase in information content and enabled vastly more complex cloud microphysical retrievals (Shupe et al. 2016).

Scientists within the ARM Program also realized that the main workhorse for quantifying the liquid water path (LWP) in the overhead clouds, the MWR, did not have the required sensitivity to accurately measure LWP when the LWP was small. This uncertainty was extremely important because (a) the median LWP for clouds is less than $100\,\mathrm{g\,m^{-2}}$ at most global locations (Turner et al. 2007b); (b) the uncertainty in the MWR-retrieved LWP was approximately $25\,\mathrm{g\,m^{-2}}$, which is fractionally quite large for a large fraction of liquid-bearing clouds (Marchand et al. 2003); (c) the longwave and shortwave radiative impact of biases in the observed LWP was largest when the LWP was small (i.e., less than $100\,\mathrm{g\,m^{-2}}$); and (d) aerosol effects on clouds are typically the largest when the LWP is small (Turner et al. 2007a). To illustrate the importance of getting an accurate measure of LWP, the error in the computed downwelling shortwave flux was between 5 and $15\,\mathrm{W\,m^{-2}}$ (depending on the effective radius of the liquid droplets) for a $1\,\mathrm{g\,m^{-2}}$ error in the LWP when the cloud LWP was less than $50\,\mathrm{g\,m^{-2}}$. This led to the formation of a focus group called Clouds of Low Water Depth (CLOWD; Vogelmann et al. 2012) that evaluated different techniques and organize and conduct a couple of field experiments, and ultimately led to the recommendation that the program needed to acquire microwave radiometers with an additional channel near 90 GHz, which would provide 3 times more sensitivity to LWP than the original two-channel MWRs that were being used by the Program at all of its sites.

Many different cloud property retrieval algorithms were developed by ARM PIs during the early 2000s, and it was clear that each algorithm had different strengths and weaknesses, in part because they used different input datasets and made different assumptions. One of the activities performed by the CLOWD group was a large, organized intercomparison of cloud properties in single-layer warm stratiform clouds from different algorithms over some specified cases. There was also a large intercomparison effort that focused on retrieved cloud properties from single-layer cirrus clouds, and another that focused on single-layer mixed-phase clouds. These intercomparisons demonstrated huge differences in the retrieved properties among the different algorithms (Turner et al. 2007a; Comstock et al. 2007; Shupe et al. 2008), even when exactly the same input was used in the different algorithms. These findings forced the Science Team to reevaluate the assumptions made in the retrievals to and investigate new ways to determine the uncertainties in these microphysical retrievals and communicate them to the data users (Zhao et al. 2012).

Another research area that gained momentum during this time period was the routine measurement of small-scale vertical motions above the ARM sites, since cloud and precipitation properties are intricately coupled with the dynamical motions in the cloud. ARM cloud radars are configured to record the first three moments of the Doppler velocity spectra (Kollias et al. 2007). These data had been used for some time to derive information about vertical motion in clouds, often for the purpose of deriving cloud properties (Deng and Mace 2008). However, in precipitating conditions the cloud radar signal is attenuated, making the accurate determination of vertical motions more difficult. Furthermore, cloud and precipitation particles are falling and have a terminal velocity, and thus algorithms had to be developed that accounted for the fall speed of the hydrometeors in order to properly determine the atmospheric motion in the cloud. Faced with these challenges, a new focus group was formed within the ARM Science Team in 2008 to evaluate methods for measuring vertical motion in clouds over a range of cloud types, from shallow warm boundary layer clouds to deep convective precipitating cloud systems.

ARM scientists worked hard to improve retrievals of aerosol optical properties in broken cloud fields and to compensate for bias errors that often emerge in these retrievals (Kassianov and Ovtchinnikov 2008). There were also studies of dust as part of the Niger AMF deployment [discussed below and in Miller et al. (2016)], where the AMF site experienced heavy dust loading at times (Slingo et al. 2006; Turner 2008; McFarlane et al. 2009). In addition to optical properties, effects of aerosols on cloud properties were also a topic of considerable study at both the fixed ARM sites (e.g., Lubin and Vogelmann 2006; Feingold et al. 2006; Guo et al. 2007; Klein et al. 2009; McFarquhar et al. 2011) and AMF deployments (e.g., McComiskey et al. 2009; J. Liu et al. 2011).

During this period, many ARM scientists began to demonstrate the value of the long-term operational nature of ARM's observations to develop robust multiyear analyses. For example, Mace and Benson (2008) developed a multiyear distribution of cloud properties and radiative heating rate profiles at the SGP, Michalsky et al. (2010) constructed a climatology of aerosol optical thickness and Angstrom exponent, Gero and Turner (2011) investigated the trends in downwelling infrared radiance at the SGP site over a 14-yr period, and Andrews et al. (2004, 2011) derived climatological profiles of aerosol scattering and absorption from in situ observations made by a small aircraft over a multiyear period. These climatologies are useful for both evaluating the variability of GCM output to ensure that it captures the entire dynamic range of the observations, as well as putting the observations from any particular field experiment into context relative to the long-term dataset (i.e., are the data from the IOP representative of what is normally observed at that site?).

The airborne measurements of aerosol optical properties were ARM's first experiment with routine airborne measurements (Andrews et al. 2004, 2011). During this period, there was an increasing sentiment in the ARM community that while intensive aircraft campaigns could be quite valuable, it was important to find ways to obtain larger sample sizes from airborne platforms. The ARM Program has now conducted multiple long-term aircraft campaigns, including the Airborne Carbon Measurement Experiment (ACME; Biraud et al. 2013), the Routine ARM Aerial Facility (AAF) CLOWD Optical Radiative Observations (RACORO; Vogelmann et al. 2012) campaign, and the Small Particles in Cirrus (SPARTICUS; Deng et al. 2013) campaign.

b. Field campaigns and the transition to the mobile facility

While some investigators were beginning to make use of the long-term record available from ARM sites, there also continued to be a great deal of effort focused on observations during intensive field campaigns. Many large field campaigns occurred at the ARM fixed sites between 2004 and 2010. The AMF, which was developed both to help sample climatic regions away from the permanent ARM sites and allow ARM to participate in large field experiments organized by other agencies and nations (Miller et al. 2016), came of age during this period and has now been deployed many times both nationally and internationally.

Major field campaigns that were held at the fixed ARM sites during this period included the 2004 M-PACE (Verlinde et al. 2007) over NSA, the 2006 TWP-ICE (May et al. 2008) above the Darwin site, the 2007 Cloud and Land Surface Interaction Campaign (CLASIC) at SGP (Miller et al. 2007), and the 2008 ISDAC (McFarquhar et al. 2011) at NSA. These field experiments were perhaps the most comprehensive IOPs that had been conducted at the ARM sites yet, with many additional ground-based instruments deployed to augment the standard ARM instruments, aircraft in situ observations, and a large number of ARM scientists and national and international participants. All of these IOPs had significant modeling efforts associated with them, with perhaps a dozen or more groups using models of all scales (from large-eddy simulation to cloud-resolving models to single-column models) focused on cases during each IOP. The infrastructure worked hard to produce forcing datasets to drive these models (Zhang et al. 2016) and to produce the observational datasets needed to evaluate the accuracy of the model simulations. Each of these IOPs had multiple breakout sessions at the spring Science Team meeting and fall Working Group meetings to coordinate research efforts and discuss results.

Although work on clear-sky radiation was diminishing during this period, there was an effort to characterize radiative absorption at far-infrared (far-IR) wavelengths that ultimately required an ''off-site'' field campaign. At wavelengths longer than about 20 μm, the lower atmosphere is highly absorbing under most conditions so it is difficult to measure detailed absorption properties of water vapor from most surface-based locations. However, the accurate treatment of water vapor absorption in climate models is essential to get the outgoing longwave radiation budget and atmospheric radiative heating correct. In regions with very low amounts of water vapor and particularly at high altitudes, the atmospheric opacity due to water vapor absorption starts to diminish. A pair of experiments called the Radiative Heating in Underexplored Bands Campaigns (RHUBC) were carried out first on the North Slope of Alaska in 2007 and then in the Atacama desert of Chile at an altitude of 5320 m in 2009 to study this far-IR region (Turner and Mlawer 2010). RHUBC-II in Chile was the first atmospheric science experiment to measure spectrally resolved radiances at the surface across the entire thermal infrared portion of the electromagnetic spectrum (3–1000 μm; Turner et al. 2012a). The marked improvements in the modeling of the absorption of water vapor in the far IR that resulted from the RHUBC experiments was shown to have an impact on the simulation of atmospheric dynamic properties in a global climate model simulation (Turner et al. 2012b).

With the deployment of the first AMF in 2005, the field campaign landscape began to change. In particular, there was a shift in emphasis from field campaigns at fixed-location sites to AMF deployments, since the AMF enabled the Program to collect data in other climatically important regions of the world. Given the time scale of several years to plan and execute a major field campaign, this transition occurred over a period of several years. This does not mean that field campaigns at the primary SGP, TWP, and NSA sites were no longer considered important or were not supported; however, there was a shift in emphasis and resources to the new AMFs as well as the Aerial Facility (Schmid et al. 2006).

This change had multiple and varied effects on the science community. For the ARM Science Team, the change meant less direct involvement in the planning of field campaigns. This change was inevitable due to ARM's new status as a user facility and the associated requirement to subject facility proposals to a peer-review process via the ARM Science Board (Ackerman et al. 2016). The other side effect of this change is that field campaign proposals were suddenly equally accessible to anyone regardless of their affiliation. Through this open process, the first AMF was deployed for five campaigns in a row outside of the United States to address key science issues (Miller et al. 2016). The PI for two of those five campaigns had no direct ties to DOE; those campaigns were the RADAGAST [Radiative Atmospheric Divergence using ARM Mobile Facility, Geostationary Earth Radiation Budget (GERB) data, and African Monsoon Multidisciplinary Analysis (AMMA) stations] campaign in Niamey, Niger, in 2006 (Miller and Slingo 2007) and the Convective- and Orographically-induced-Precipitation Study (COPS) deployment to the Black Forest in Germany in 2007 (Wulfmeyer et al. 2011). All of these AMF deployments included a significant contribution from ARM's international colleagues. Of course, scientists connected with the ARM Program continued to be very involved in these deployments, often as PIs, but now the doors were open to the international climate science community. A result of this was to significantly broaden the interest in ARM both in the United States and internationally.

Another fundamental change associated with the shift toward operating the AMFs was the duration of field campaigns. Consistent with ARM's goal of collecting climatologically significant datasets, the AMFs are typically deployed for about a year at a time. Traditional intensive field campaigns provide enhanced measurements focused on a specific problem for a short time but AMF deployments offer a standard set of ARM measurements for (typically) an annual cycle. Analyses of AMF data have shown that these extended observation sets can reveal characteristic of a locale that are not apparent from the short time series typical of intensive field campaigns (e.g., Slingo et al. 2008; Rémillard et al. 2012).

c. Linking observations with models

As noted earlier, improving climate models is a central goal of the ARM Program. The process of improving parameterizations in climate models is a complicated one that often involves a combination of observations, analysis, high-resolution modeling, and global-scale modeling. Through the application of special datasets and through ongoing efforts to link model developers with observation data, significant improvements were made in model parameterizations during the 2000s, which is summarized nicely by Randall et al. (2016). As a single example, in the most recent version of the NCAR–DOE Community Atmosphere Model version 5 (CAM5; Neale et al. 2010), several improvements have made important use of ARM data and associated research, including using an improved radiation scheme (Mlawer et al. 2016) and better representation of cloud and aerosol processes (e.g., X. Liu et al. 2011b).

In climate models, radiative transfer involves the interaction of solar radiation and terrestrial infrared radiation with the earth's atmosphere and land surface. Radiative transfer models tend to take a lot of computer time. A version of the RRTM radiative transfer model, grounded in many years of ARM science, was developed to run efficiently in GCMs (RRTMG; Iacono et al. 2008) and included in the CAM5 along with several other global models. RRTMG has also been integrated with a novel technique for capturing the interaction of radiation with clouds that improved both efficiency and accuracy (Pincus et al. 2003; Mlawer et al. 2016).

Microphysical parameterization changes in CAM5 included the addition of a three-mode aerosol scheme and a two-mode microphysics scheme. The three-mode aerosol scheme represents the diversity of aerosols in three size ranges. This parameterization has proved to be efficient and accurate when compared to more complex aerosol schemes that would not be computationally feasible to run in a climate model (Ghan et al. 2012). A two-moment cloud scheme describes cloud droplets in terms of water mass per unit volume as well as the number of cloud droplets in that volume. This represents a significant advance over single-moment treatments of clouds that only determine the water mass (Gettelman et al. 2008). Additionally, Bretherton and Park (2009) developed a new moist turbulence scheme tested with a variety of field observation data including data from M-PACE. These parameterization developments represent a significant advance in the realism with which these processes are represented in climate models, which is expected to improve the model's ability to accurately simulate climate change.

To accelerate the use of ARM data for climate model development, the ARM Best Estimate (ARMBE) product was developed during the mid-2000s (Xie et al. 2010b). The ARMBE product provides simplified access to ARM data by packaging critical geophysical quantities derived from ARM observations into a convenient file structure with a consistent temporal resolution. The ARMBE product made ARM data drastically more assessable to the modeling community, and thus facilitated the evaluation of model simulations with ARM data.

The development of the ARMBE product was in response to an increasing emphasis on connecting the climate modeling community to ARM data. Using ARM data to improve climate models had always been a central goal of ARM but during this period (c. 2004–08) this goal took on a greater sense of urgency. The ARMBE product has proved to be very popular within the climate modeling community where it is used both by individual investigators and as a model evaluation dataset (e.g., Ahlgrimm and Forbes 2012; Song et al. 2013).

4. The Atmospheric System Research Program

In 2010, as the first Recovery Act instruments were being deployed in the field, the ARM Science Team also underwent a significant change. The DOE Climate and Environmental Science Division (CESD), which is the division of DOE within which ARM resides, was working to better integrate its climate research programs. At that time, CESD included two atmospheric observation programs with related objectives: the ARM Program and the Atmospheric Science Program (ASP). The ASP focused on the life cycle of aerosol particles including aerosol nucleation, mixing states, aggregation, and growth. ARM also included an aerosol component but it was largely restricted to radiative properties of aerosols and the role of aerosols in cloud formation. However, with this dual program structure in CESD, there was some risk of activities falling between the two programs or of having duplicated effort. So, in 2010, DOE merged the ARM Science Program and the ASP to form the Atmospheric System Research (ASR) program. In many ways, the structure of ASR was modeled after the former ARM Science Program but encompassed the full scope of ARM and ASP. DOE

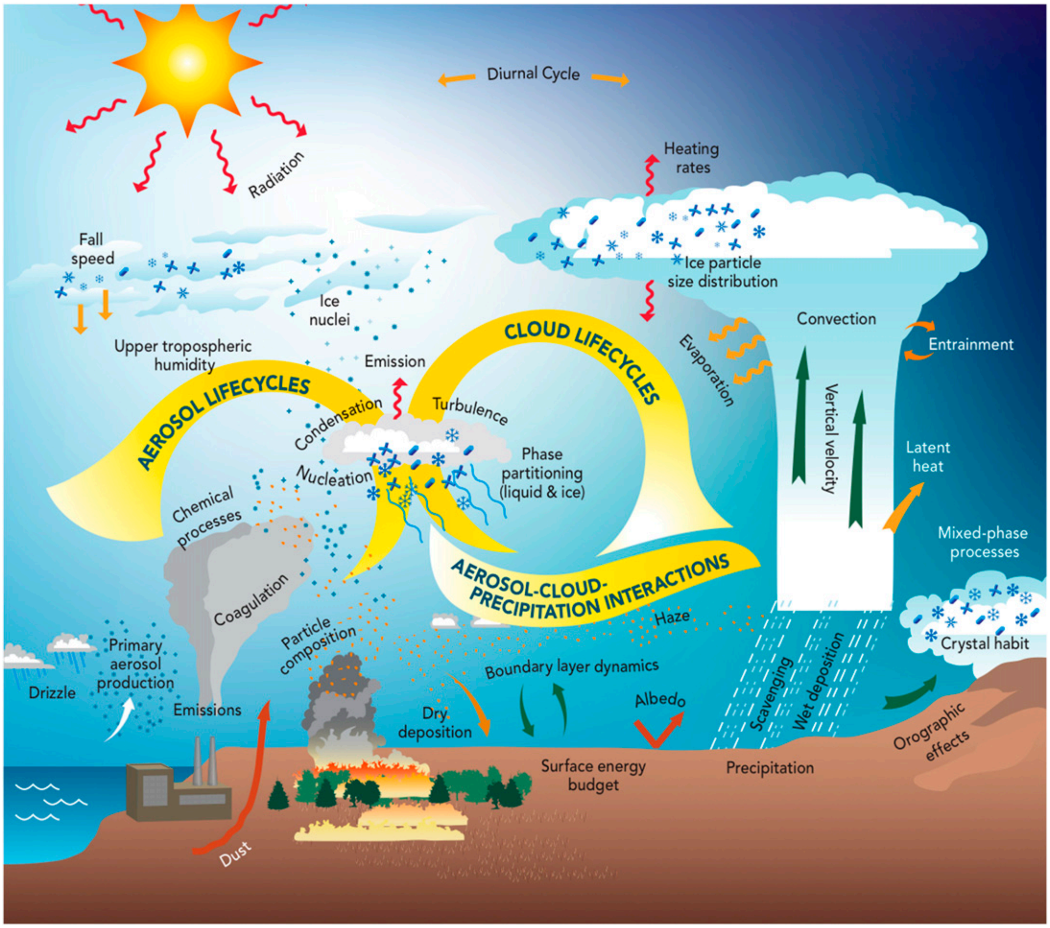

FIG. 4-4. Depiction of atmospheric processes related to clouds, aerosols, and their interactions from the ASR Science Plan (U.S. Department of Energy 2010).

management solicited the input from the ARM and ASP chief scientists, the SISC, and other scientists both within and external to the two programs in the development of the new ASR Program.

The scope of the new ASR Program was articulated in a Science Plan published in 2010 (U.S. Department of Energy 2010). In addition to an increased emphasis on aerosols, there was also a distinct shift toward better understanding of the range of atmospheric processes that need to be captured by numerical models (many of these processes are illustrated in Fig. 4-4, which is the cover of the ASR Science Plan). Previously, the emphasis had been on characterizing the atmospheric state, cloud properties, and aerosol properties, and in particular their radiative characteristics. With the shift to processes, questions such as how the atmospheric state and the associated cloud, aerosol, and precipitation fields evolved came to the fore. To help focus on process-related issues, the ASR Science Team was organized into three working groups: cloud life cycle, aerosol life cycle, and cloud–aerosol–precipitation interactions (Fig. 4-1). These working groups illustrate the centrality of clouds and aerosols to the ASR Program and to ARM. Unlike the previous organization of the ARM Science Team, there were no longer working groups specifically focused on modeling or radiation. Instead, these activities were integrated into each of the three working groups. Each working group has two chairpersons, one representing the observation community and one representing the modeling community. These working group chairs serve as the ASR representatives on the SISC.

These changes were not without their challenges, however. While the ARM science community had several years to adjust to the user facility model, the ASP Science Team, which had been working with a field campaign measurement model up to that time, had to make more rapid changes. Furthermore, the ASP measurement approach tended to rely more on research-grade instruments deployed for short periods of time to obtain the needed detailed information on composition and structure of aerosols; these instruments were not always well suited to the ARM model of continuous operation.

The Recovery Act (Mather and Voyles 2013) provided the necessary means to greatly enhance the aerosol observations at the fixed ARM sites and the AMFs to provide the measurements needed by the aerosol life cycle working group. However, there was also a recognized need that additional chemical measurements may be required for some experiments. Thus, through the Recovery Act, a Mobile Aerosol Observing System was developed to provide a core set of aerosol chemical measurements. Additional measurements for particular applications could then be requested for intensive field campaigns, such as for the Carbonaceous Aerosols Radiative Effects Study (CARES; Zaveri et al. 2012). Other instruments, such as Doppler lidars, are also proving very useful in connecting surface measurements of aerosol properties to those aloft by allowing the evolution of the mixing within the boundary layer over the diurnal cycle to be better understood.

5. ARM–ASR future directions

The scope of the ARM facility and its science partner, the ASR, has expanded considerably since the early days of the program when the focus was on understanding the radiative characteristics of the current state of the atmosphere. However, even at the outset, the stated goals of the ARM Program included a need to improve the understanding of the distribution of clouds and their impact on the earth's radiation balance (U.S. Department of Energy 1990). Understanding this distribution requires a study of a wide range of atmospheric processes, and this has become the focus for ASR and is being supported by measurements from ARM.

The emphasis on characterizing and improving our ability to observe and model the life cycles of clouds and aerosol is beginning to gain traction within the ASR science community. A great deal of work is still needed in important areas such as the properties and life cycle of mixed-phase clouds; the organization of tropical convection; the role of dynamics (especially small scale) in cloud, aerosol, and precipitation processes; and the evolution of aerosols from precursor gases and nucleation through their growth phase and ultimately their impact on clouds. Making progress in these areas is critical to improving the representation of clouds and aerosol in climate models and so will likely continue to garner a great deal of attention over the coming years.

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